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APPLICATIONS OF DIGITAL CORRELATION TO THE MEASUREMENT OF VELOCITY BY LIGHT SCATTERING

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ABSTRACT

Scattered light may be studied efficiently by correlation of individual photon detection times. Available photomultipliers and fast digital correlators make these techniques applicable to subjects as disparate as molecular biology and aerodynamics of rotating machinery.

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1.0 INTRODUCTION

There are many areas where the measurement of velocity is the key to understanding some phenomenon or improving some machine. Measurements which do not modify the situation are highly desirable and optical scattering may often come into this category. In the last ten years it has become possible to extract good data from very low light levels by observing single photons. Fast correlators have led to new and rapid experiments in the United States and Europe, which have advanced the state of various arts, from molecular biology to the manufacture of aero-engines. This paper outlines the techniques, state-of-the-art and certain applications of this expanding approach to measurements.

2.0 BACKGROUND

Light is conventionally defined as electromagnetic radiation in the wavelength range from 400 nm to 750 nm. For historical reasons, it has been usual to identify the information in such a beam of radiation as dependent upon its frequency, but this is only useful if all the rules are purely classical. The concept is useful for electromagnetic radiation from radio wavelengths to those as short as the infrared. In the ultraviolet and regions of shorter wavelengths, a more useful measure of information is power because the classical assumptions must be replaced by the quantum mechanical rules of discrete energy packets. The "gray area" in the optical region has been one where either classical or quantum concepts have been used according to the problem in hand.

Until this century it was only convenient to measure mean light flux as an analog parameter, and when it became possible to identify individual quantum arrivals, the "shot noise" was considered to be detrimental. Great progress has been made with optical detectors, but it is only really in the last decade that the arrival time of individual photons has taken on significance. The trend towards single photon detectors has been boosted by the invention of lasers, the second industrial revolution (based upon the switch rather than the wheel) and the properties of modern photomultipliers. That the energy of a typical optical photon should exceed that of molecular vibration at room temperature by a factor of $\sim$40 indicates that, with proper selection of cathode materials and attention to electron focusing, envelope purity, screening and the many other engineering details, it is possible to achieve almost noise-free photon detection[10,22].

Discrimination of photon detections yields a train of identical events (one photon is very much like another insofar as it liberates a photoelectron, or it does not) which is no more than the required input for digital circuitry (Figure 1). Thus nature

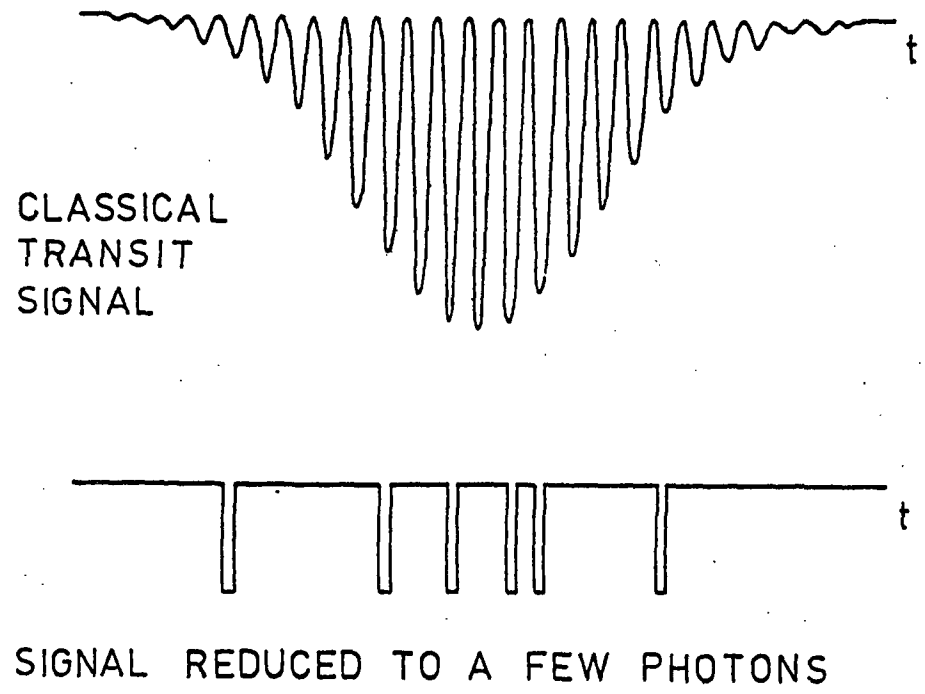

Figure 1. Quantum Effects On An Optical Signal With Reduced Intensity.

has given us a brilliant analog to digital converter such that the arrival times of photons contain all the information. Immediately we see that "intensity" is the mean rate of photon arrivals, and that the arrivals obey a distribution function which tells much about the source and history of photons. Early work pointed out that the photon arrivals from a pure thermal source correspond to Gaussian fluctuations of electric field strength and from a perfect laser far above threshold follow Poisson statistics[24]. Other physical processes interacting with a photon stream prior to detection affect the statistics of photon arrivals and by measurement of these statistics a powerful diagnostic tool is conceived for the examination of these processes[7,8]. Of course, there is no more information in the light beam than there ever was, but the retrieval efficiency available through this approach makes a large number of physical measurements accessible.

3.0 REALIZATION

A time series of identical events can carry information as the mean event rate and as the distribution function of intervals. Much of this latter is conveniently accessible via the autocorrelation function of arrival times. The digital correlation of a number sequence with finite limits is conveniently defined as

$$R = \frac{1}{N}\sum_{k+1}^{N} (n_k)(n_{k+j})$$

where the k^{th} number is the accumulation of events in the interval $[(k-1)\Delta t, k\Delta t]$. Although more correlators are becoming available, this author knows of only one commercial machine at present which operates in this digital mode at a speed to be useful for many of the applications to be discussed. There exists a number of machines in private hands which claim higher speed than the Malvern Digital Correlator, but these would currently only be of interest to someone who wished to research this technique rather than use it.

Certainly the future lies in higher speed; by that we mean faster and better photomultipliers, shorter correlation delay increments and more satisfactory and quicker readout and interpretation of the correlation function. The operation of a digital correlator may be summarized by Figure 2. The mathematics of correlation is available in the standard texts and those aspects pertinent to this discussion are mentioned elsewhere in the required detail[7,8,27,30]. Many strange and interesting cases which occur in practice are beyond the scope of this note. A significant, but still inadequate, literature is building up on the various properties of correlation functions obtained from each of the various methods of using the above philosophy. The more serious limitations that inhibit this technology center around the properties of presently available photomultipliers. Those properties which are most desirable are high speed, low correlation and low noise. Minute dissection of these constraints shows

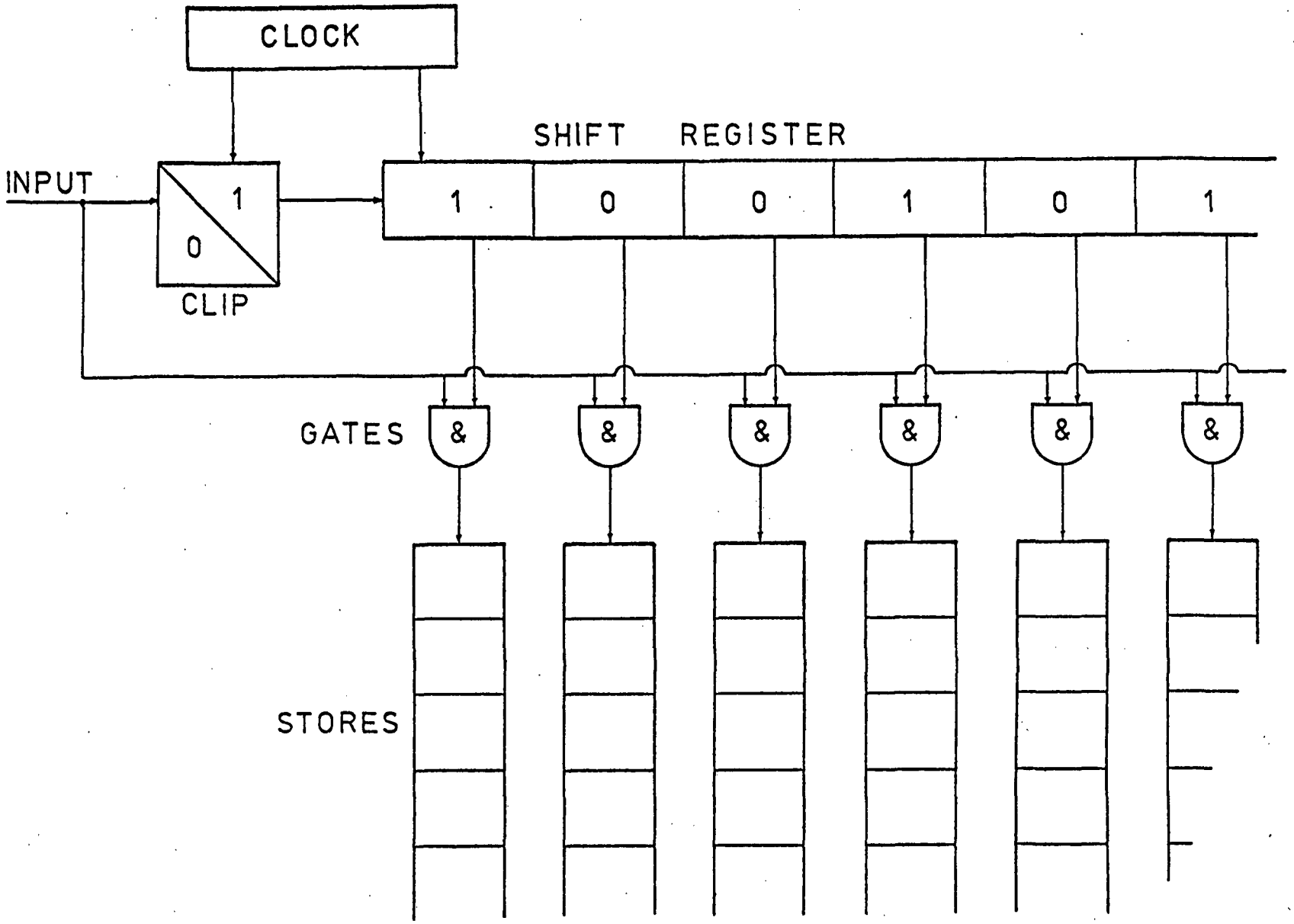

Figure 2. Schematic of a Single Bit Clipping Correlator.

that they are not in practice mutually exclusive but a rough explanation shows where the problem areas lie. The anode pulse derived from each photon which releases one or more photoelectrons from the cathode should be of rapid and constant rise time, constant amplitude, constant delay after photon impingement on the cathode and not initiate any subsequent event or signal. Dead time should be as short as possible. High gain is desirable, implying a large number of dynodes. This is not only the most efficient form of signal amplification, it means that events arising within the photomultiplier are less likely to operate the discriminator of the anode pulse. A good modern photomultiplier is quite capable of delivering a five volt pulse of 2 ns rise time into 50 ohms from a single photon. Some experience is often necessary in getting the best out of photomultipliers but it is sufficient here to state what may easily be achieved. (Appendix).

It is probably not appropriate to go into great detail about what ideally should happen between the conceptualization of a quantum field estimator and the input of a digital event to a correlator. This is explored in the literature[24]. To those unfortunates condemned to extract answers to n significant figures from the use of this technique, those assumptions must be examined in more detail and it is only recently that the problems are being analyzed, and the extent of variation to be expected from the behavior of real devices compared with theory.

Even though it sounds likely that the various limitations should prohibit the realization of good data, this is far from the true situation. In practice the precision, and indeed accuracy, of measurements obtained from very low light signal systems is found to be at least as good as, and in some cases rather better than, those conventional information retrieval techniques which require many times more scattered light. To achieve these results it is often necessary to be rather careful with the optical configurations with respect to rejection of scattered light which does not contribute to the required information.

4.0 VELOCITY MEASUREMENT

Three types of experiment have become commonly used in conjunction with photon correlation of the signal:

1. Spectroscopic applications involve a laser beam illuminating a volume of space which contains in general several scattering entities. These may be large or small molecules suspended in or of a liquid, or even living organisms. Basically, scattered light suffers a loss of temporal coherence because of multiple interference effects between scatterers moving with respect to each other. It is not required to discuss spatial coherence properties in this paper because we are implying single channel point detectors whose physical size has been chosen to be appropriate to the experiment. From measurement of the autocorrelation function of the scattered light signal, the temporal coherence properties may be examined and from simple models, velocities may be obtained. The advantage of using a digital or photon correlator here is twofold; firstly, the high speed is essential for good measurement of small particles which may result in short correlation times because of rapid movement, and secondly, the light level used may be extremely low and hence not modify the situation being examined.

2. Real fringe anemometry has been widely used for the last ten years for measurements of fluid flow properties in many different applications. The common techniques for signal analysis and information retrieval often demanded large laser power and considerable subtlety in electronics to get good data in many of the difficult situations of most commercial interest. The improvement of two to four orders in signal processing efficiency has made a significant impact on those areas where the answers are of financial importance.

3. Recently, an advantage has become apparent in redirecting the available laser light from a circular area of fringes into two small spots or cylinders of higher intensity. The largest single

advantage is rejection of flare from adjacent solids, and this makes the system a good choice where sampling spaces are restricted, in turbomachines for example. The advantages of digital correlation here may be seen in two modes of operation. If sufficient light is available to observe a particle transit as having a clearly defined peak time, then this may be used as a cross-correlateable event; or if only a photon or two is available from each transit of a spot, these may be cross correlated directly to yield a mean transit time probability. Once again the high speed of the correlator is the advantage whereby high velocities are accessible without a severe penalty of spatial resolution.

We may look at some of the above experiments in more detailed examples and see what the concepts of photon correlation and fast digital correlators have done to extend the range of feasible experiments. In many cases it is the ease with which a particular experiment may be performed which has become a great advantage. Speed and ease are particularly important in medical applications. In vivo experiments require brevity and convenience and many experiments on biological samples must be performed before the sample changes its properties due to degeneration or mere removal from the living environment.

5.0 SPECTROSCOPIC APPLICATIONS

One way of regarding a photon correlator is as an ultra-high resolution spectroscope. The present machines, with an acquisition interval of 50 ns, and machines to be available in the future with intervals of 10 ns, are capable of resolving linewidths very many orders narrower than any conventional spectroscope. Because the measurement is made in a time domain, the resolution criterion is easier to achieve at narrower line width, thus requiring a faster correlator to achieve resolution of comparable order to the best Fabry-Perot etalons. The resolution available with a good confocal etalon in optimum adjustment is claimed to be 5 to 10 MHz with a free spectral range of about 1 GHz whereas the present correlators barely overlap this range, being more satisfactory at resolution better than 3 to 1 MHz or less. Resolution may be increased by increasing the maximum delay of the correlator but often the resolution indicated by the longest correlation time may not be achieved because of inadequate stability in the laser source. By running the experiment for a long time it is easy to realize a high signal to noise ratio and hence a good profile shape for the equivalent spectral distribution. This is not so much a limitation of the principles of photon correlation as a requirement to observe the process for a sufficiently long time that it may be considered statistically stationary.

Given that the effective laser linewidth is sufficiently narrow that the test situation dominates the broadening or reduction of temporal coherence, many formerly detailed and exacting measurements become very simple.

Some examples may be of interest. The light scattered from very pure liquids indicates molecular properties. Brillouin scattering may be observed and measured and photon/phonon interactions characterized[7]. It is possible to obtain exceedingly accurate measurements of diffusion in pure liquids and to explore the variation of that parameter with temperature. Good measurements can be

obtained in experiments lasting no more than milliseconds or even microseconds and with very small samples of sizes down to microliters[7]. Care must be taken to assure the absence of any large contaminating particles in the sample as these will destroy the applicability of the measurement. It is important to note that the measurements of decay of temporal coherence depend ultimately on the velocities of constituent elements in the volume from which scattered light is received. Basically, the measurements are obtained here as the heterodyned frequency of the light scattered from moving particles with that scattered from something considered stationary. In practice, there is almost always sufficient source of stray light to assure that this will happen. In cases where more control is desired, a reference beam from the source laser may be introduced separately. What is really being measured here is the Doppler broadening or the intensity fluctuation spectrum. If there are many scatterers present simultaneously, the central limit theorem assures Gaussian statistics, but great detail is available in the literature[7,8,24].

When the molecules of interest are suspended or solvated, their properties become more difficult to assess by conventional methods. Light scattering methods at the high resolution now available allow physical chemists to study the properties of large and complex molecules without physical interference with what may be a state of low stability. The behavior of molecules (with both solvent seeking and solvent hating parts (amphiphilic)) in dilute solutions at various ionic strengths yields valuable data about the detailed processes involved in micelles, their size, shape, structure and properties[8]. Many molecules have "heads" and "tails" as far as the affinity for a solvent system is concerned, and the possible ways that complex forms may arise in such a system are interesting and important. Micelles arise where a number of solute molecules prefer their own proximity to that of the solvent; for example, a structure of many molecules with polar tails may form a "heads in"

structure in aqueous solution and an inverted "tails in" form in a non-ionic solvent. The size and shape of these structures depends on the nature and concentration of the solute/solvent system, of course, and also on temperature and the degree of ionic screening available in solvents of different ionicities. Zulauf at Basel[38] is working on micelles in ionic and non-ionic systems and de Gennes of the French School who provided much of the theory is presently working on micellar phenomena.

A similar example is the study of phase transitions, particularly in such complex physical structures as liquid crystals with transition between nematic and smectic phases[8]. Exploration of critical opalescence and transition phenomena is invited by this technique. Photon correlation has fired considerable enthusiasm for areas where experiments were formerly difficult or intrusive, modifying those very phenomena which were of interest. The same type of analysis can be applied to many other types of molecules. In some cases the structure of molecular chains may be observed during the polymerization processes because observational experiments may be performed very rapidly.

In the life sciences, it is often difficult to produce large and/or long lived samples of the molecules of interest and speed and economy of sample are very important. Molecular diffusivity may be measured with great ease. The spectroscopic technique assumes that the particle velocities are completely random in direction, and if this is a reasonable assumption, the properties of entire cells or small creatures may be measured. The behavior of bacilli and spermatozoa can be quantified. The latter is of special interest in repsect of financial reward as the motility of spermatozoa is indicative of the quality of a sperm sample. It is certainly cheaper to fly sperm samples about the world than to move animals, and it is good to have the best ways of assuring quality control. There is some suggestion that sperms of different sex have different motilities, and if this could be exploited, then there is the

potential for considerable economies of stock breeding and genetic improvement. Again because the measurement may be performed rapidly and with a sufficiently low light level not to affect the measurement -- even where the system under examination may have light-sensitive behavior -- it is possible to observe phenomena which were formerly neither suspected nor understood.

Professor Chu at Stonybrook[9] has very recently made measurement of both rotational and translational diffusion coefficients of bulk tRNA from bakers yeast[23], the shape of molecules and their change of shape with temperature and ionic strength of the supporting solvent system. This method included conventional photon correlation spectroscopy for translational diffusion and more subtle depolarization measurements for rotational properties. He used resolution down to 1 ns for measurements of the rotational relaxation (typically 30 ns) the details of which are soon to be published.

A small modification to the geometry of the reference wave in the spectroscopic experiments enables velocities to be directionally resolved with the immediate extension to the measurement of electrophoretic or photophoretic mobilities. Measurements have been made inside living cells of plants and animals and of the complex patterns of movement in such unkindly named entities as slime molds[8]. The measurements of preferentially directed velocities falls more properly under one of the next categories.

6.0 FRINGE ANEMOMETRY

The heterodyning of the scattered wave with a reference wave is equivalent to the production of virtual fringes associated with the scattering volume. The more common system is to illuminate the sample volume with two coherent laser beams derived from the same laser, thus producing "real" fringes, which are, of course, no more real than the others but give a very useful conceptual model. The choice of "real" or "virtual" fringes is discussed in the literature, but the most important single factor in the choice of which to use is the number of scattering centers in the sampling volume[11]. In the case of less than one, the real fringe illumination is the better choice. In the case where there are more than five (say) scatterers always present in the volume, it becomes more effective to use a reference beam, virtual fringe system. Sadly, there is a region between these regimes where there is no unequivocal choice and each experiment must be judged upon its own merits. This review paragraph illustrates the approach of classical laser anemometry[12,13].

In principle the extension of conventional real fringe anemometers (where the derivable signal is adequate for other processing techniques) to the use of photon correlation involved no significant hardware changes. In practice it is necessary to take much more care over certain factors such as the rejection of stray light from all sources by the careful design of optical stops and the use of narrow band filters. It is usually necessary also to select more appropriate fringe spacing and number in order to achieve the most advantage, often to the extent of requiring the selection of an optical layout optimized for each application. This may not always be necessary but will always repay the effort with better data.

In general, it has been technically feasible and often quite easy to make good measurements in transparent liquids because most

contain sufficient identifiable scattering particles which give rise to a signal significantly above any background. Measurements of blood flow have been made in animals, but since the advent of photon correlation it has been possible to work with such low light levels that measurement of blood flow have been made in the human retinal vessels without risk of damage[8].

In gaseous systems there are again many real advantages in working with less light than has been conventionally thought necessary. The two ways of looking at the advantages are that they make experiments possible where they had not been performed before and secondly that they make easier an already used experimental technique.

It is convenient here to summarize the ways in which the significantly higher efficiency of signal retrieval may be taken:

1. Smaller scatterers -- desirable in gaseous systems as they follow the flow more accurately than larger particles.
2. Smaller laser -- cheaper, more robust, less liable to modify the situation being observed.
3. Smaller light collection solid angle -- mechanical or geometrical constraints may make a large cone infeasible.
4. Backscatter -- instrument is more compact and more easily traversable. Backscattered signal amplitudes from particles in the size range of interest are usually much smaller than forward.

Any combination of these signal economies may be taken up to the limit of the production of adequate velocity estimates[31].

It has been stated that from one transit of a single scatterer it is possible to obtain velocity measurement to about one percent accuracy from 60 to 100 photons[8].

The technique of laser anemometry is well known and documented[12,13] but is by no means fully explored. The many and various earlier techniques which exist for retrieving information from the scattered light signal rely on rather more light than may

be obtained from some of the situations which are both more difficult and of more engineering interest. Of the usual techniques of electronic processing such as spectrum analysis, tracking, counting, filter bank, the operating concept of the system is fairly complicated and interpretation of the output superficially quite direct. In photon correlation, the correlation concept is extremely simple but the difficulties of relating the correlogram to the required data have been a deterrent to wide adoption of the method by engineers. In fact, the same or analogous difficulties are present with the other retrieval methods but the problems encountered there are rather better concealed.

Several discussion meetings in England have labored over the problem of correlogram interpretation (Figure 3) and many methods have been suggested, from a direct and very useful method of assessing mean flow and turbulence with up to third significant moment[34] but with rather low accuracy, to a Gram Charlier analysis[5] of rather more complete velocity characterization but no better physical model. Intermediate analysis methods have been published[21] and are still under development. The algorithms are becoming simpler and more powerful[1,2,19].

To this point the photon correlation principle has been used to accumulate averages over the velocities indicated by light scattered by particles during the experiment. The nature of the average formed is always a complex and contentious point of discussion, but it seems that in true incompressible flow with isotropic Poisson particle loading that the measured velocity properties are those of the fluid to first order accuracy in mean velocity and turbulence. These points have been[6] and will continue to be discussed for some time[17].

Of more recent and more demanding interest has been the need to look at time varying properties of the signal. It is becoming more important to use a method capable of retrieving velocity and

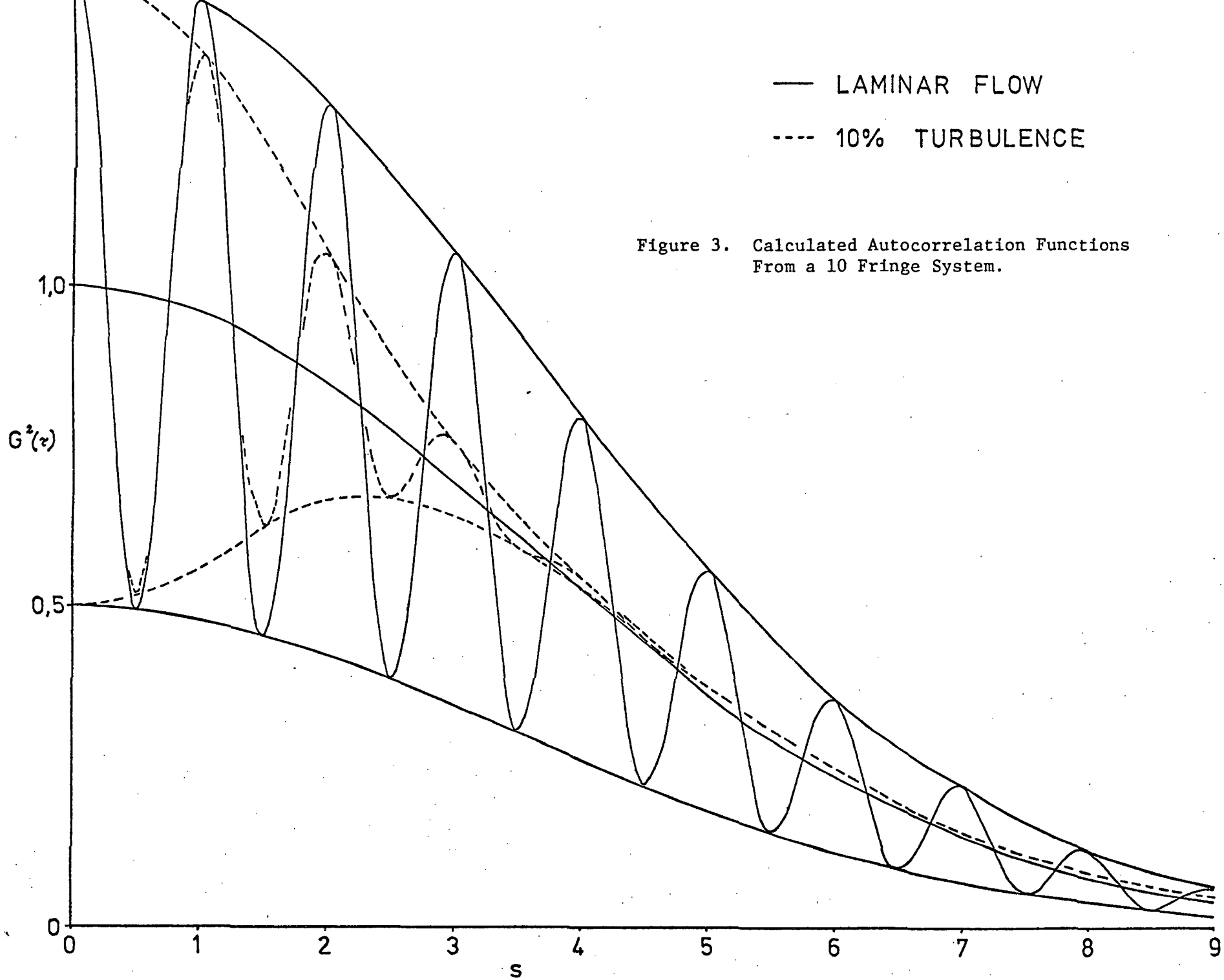

Figure 3. Calculated Autocorrelation Functions From a 10 Fringe System.

turbulence spectra and to this end the principles of photon correlation are still an advantage; but because of the internal organization of presently available machines, this has only been exploited in some cases[19,20]. Aside from the possibility of semi-continuous realization of an instantaneous velocity propounded in the last two references, it seems a current fashion to attempt to extract and process completed correlograms to obtain a sequence of estimates of velocity (and estimates of the precision of each) at pre-selected times thus avoiding many of the problems of random sampling[15] and biasing[6,18]. This author ventures no opinion as to which method will find more support among the future users.

Early elegant theory and more recent practical results from She[26,27,3,4] augment wind speed measurements by Pike[16]; thus three approaches have been used to measure this parameter, backscatter of CO_2[16], laser radiation backscatter from real fringes[3] and recently a transit system of which more is written in the next section[4]. She[28] has extended these principles, in combination with resonant fluorescence, and suggested the feasibility of measuring velocities of individual atoms. Many people had been working on laser anemometry applications in areas where there was a serious engineering need combined with a hostile environmental situation. Early methods had proved difficult for reasons which are well documented, and the availability of photon correlation extended applications significantly[29,30] in aero-engines and the installations for development and testing of component assemblies. Abbiss[1,6] has pioneered the application of fringe mode photon correlation anemometry to transonic and supersonic wind tunnels and has done excellent and extensive work on automating the traversing, data acquisition and processing. He has recently performed some three-dimensional velocity measurements in a low speed tunnel giving a complete 3D characterization of the velocity flow field. This work was performed in a 4 ft. by 3 ft. tunnel with typically 30 ms^{-1} flow speed. He has obtained data in the vortex cores of wake flow

with typical best measurement times of 25 ms giving about 1% accuracy. Using laser anemometry, Wigley[37] at Harwell has recently made measurement in a stratified charge engine operating with combustion at 2000 rpm. Many excellent measurements have been made without photon correlation and constitute a large and impressive literature. The introduction of photon correlation represent one possible way to go when uncontrollable factors make other types of measurement less than straightforward.

Recent applications of photon correlation to velocity measurement have included the work of Danielsson[6] who has constructed rotating optics to measure gas flows in a rapidly rotating annular chamber and Wang[35] who has made measurement near the surface of a fluidized bed with turbulence intensity of the order of 10% - 20%.

7.0 TRANSIT ANEMOMETRY

A number of years ago it was suggested[33,32] that the transit time of a small particle between two illuminated regions of space be measured as a method of inferring velocity. Early ideas considered two sheets of light, and the transit time of a particle moving from one to the other gave speed or resolved velocity. In order to obtain true velocity in a direction chosen by the experimenter, the light was concentrated into two nearly parallel cylinders whose cross section appeared as two spots. The intuitively expected reduction in number of transits did not occur because the same light power provided more intensity, and smaller particles, of which there are usually many more, then scattered an adequate amount of light. The immediate and most significant advantage in replacing an extended fringe system with two bright separated cylinders is the potential for rejecting background flare from material surfaces in close proximity to the sampling volume. The appropriate choice of optical stops can give a theoretical signal/flare improvement of three to five orders and careful design shows that two to three orders are easily realized in practice[17]. Extensive work[25,14] has led to competent hardware construction and very useful measurements in formerly inaccessible areas. This author has extended the above ideas to use the photon correlator and photon correlation principles and a brief note on some application trials was included in Reference 17. The very impressive results obtained by this technique and the machines designed to exploit it illustrate a wide potential application of the principle.

It is appropriate to list some properties of a typical transit instrument of which several already exist. Typical sampling volumes are 0.5 to 1 mm in all directions, the systems require access from one side only and use co-annular backscatter. Because of the highly focused spots, a relatively small laser has been adequate.

Whether seeding is required is dependent upon the application and the observation time available. This author has obtained good measurement of velocity and fair estimates of turbulence in an unseeded flow at 800 ms^{-1} and 2200 K in somewhat under 60 seconds with a 15mW HeNe laser using photon discrimination and correlation techniques. With the same machine (Figure 4) measurements have been made in a boundary layer (Figure 5) to within 100 μm of a stationary wall and in a gated time frame to look at inter-blade and wake flows in a fan[17]. In rotating machines (Figure 6) where time gating is used to explore flow fields in the passages between rotating blades, and the machine operation time is very expensive, it may be necessary to seed the flow or use an Argon laser to reduce data collection time. The direction of flow, a very important property in compressor and turbine design, is obtained easily and with high accuracy. Using relatively simple data reduction techniques, 0.5° arc and 0.5 percent on direction and velocity are easily achieved as resolution and with careful work may be taken as limits of accuracy. The two spots are made to rotate about a common center to explore the distribution of velocity probability in different directions. The spot orientation rotation is easily organized and controlled by the same technique as the mechanical traversing and from these data a complete contour map of velocity probability in velocity space may be constructed. If the examined phenomena are periodic, simple gating of the correlator enables statistical averages to be accumulated at different phases of the cycle.

It should be stressed here that all the measurements made by this machine are statistical and Mayo's triply stochastic model[19] is useful: the randomness of quantum realizations of optical field intensity, the randomness of particle occurrences within the flow and the randomness of the turbulence. In the last two of these models the randomness is severely modified by ordering properties in the machine or situation in question and in general it is these that we require. Another interesting property of the system is that

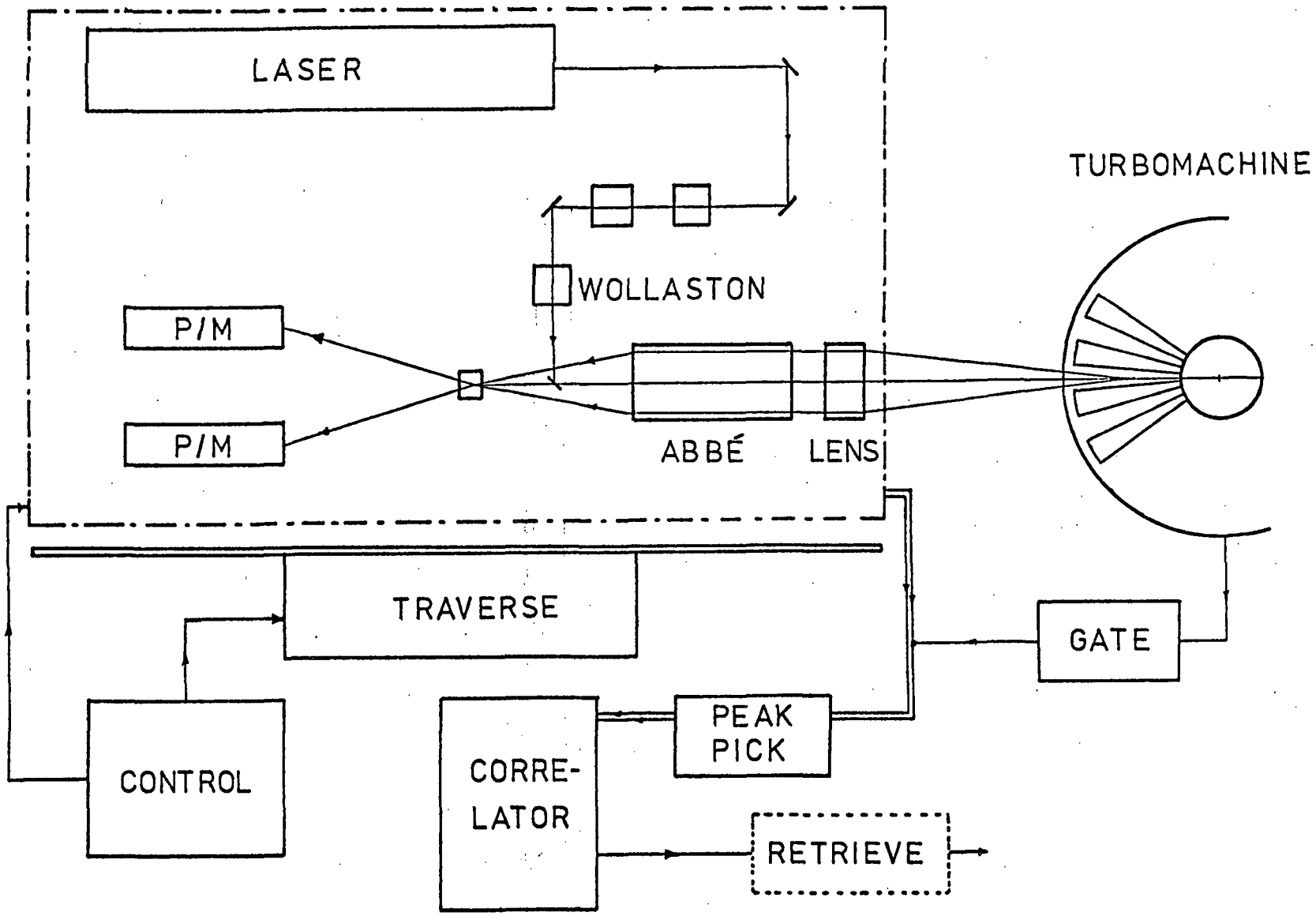

Figure 4. Schematic of Transit Anemometer System.

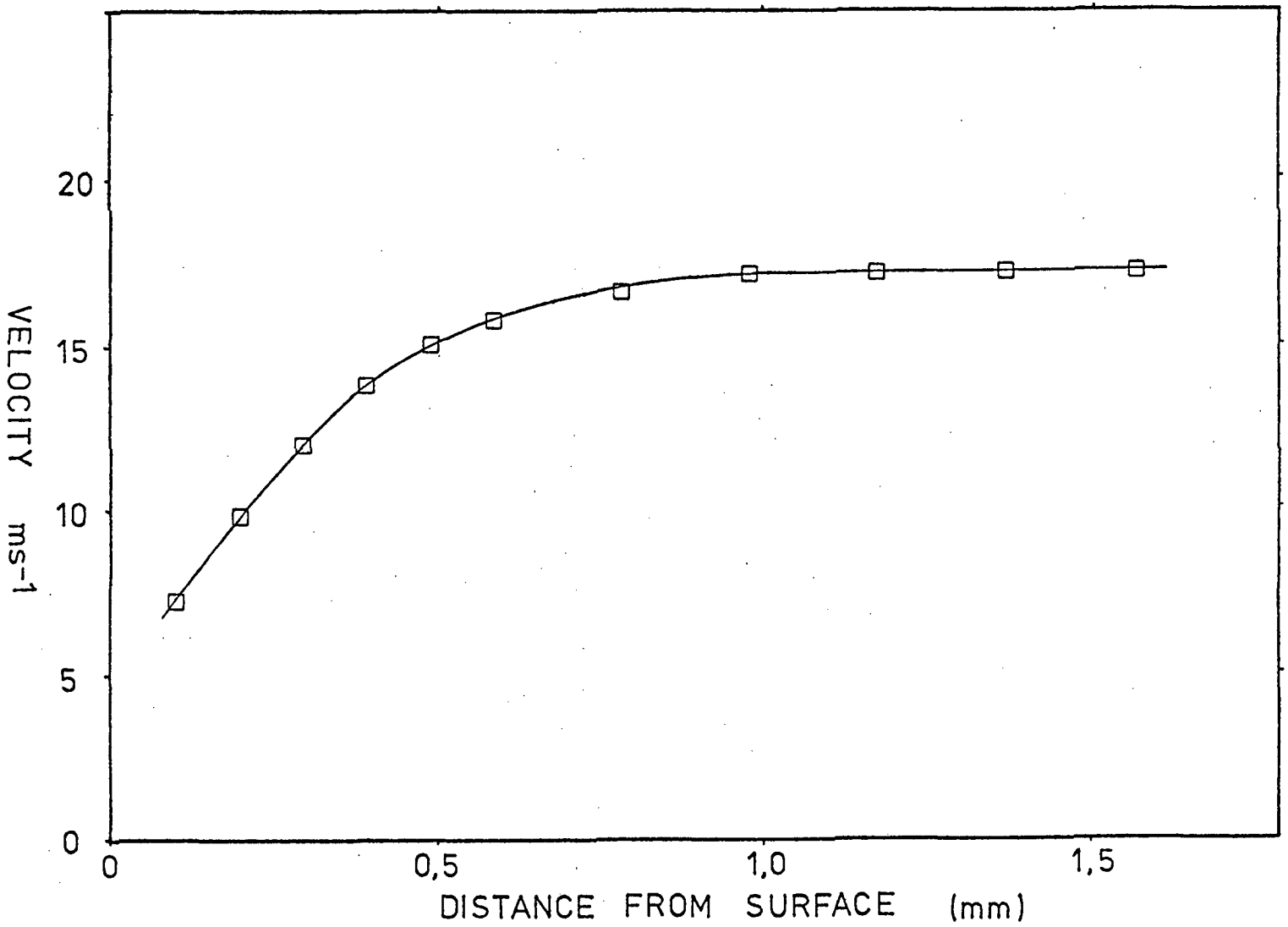

Figure 5. Boundary Layer Traverse on Pressure Surface of a Turbine Cascade.

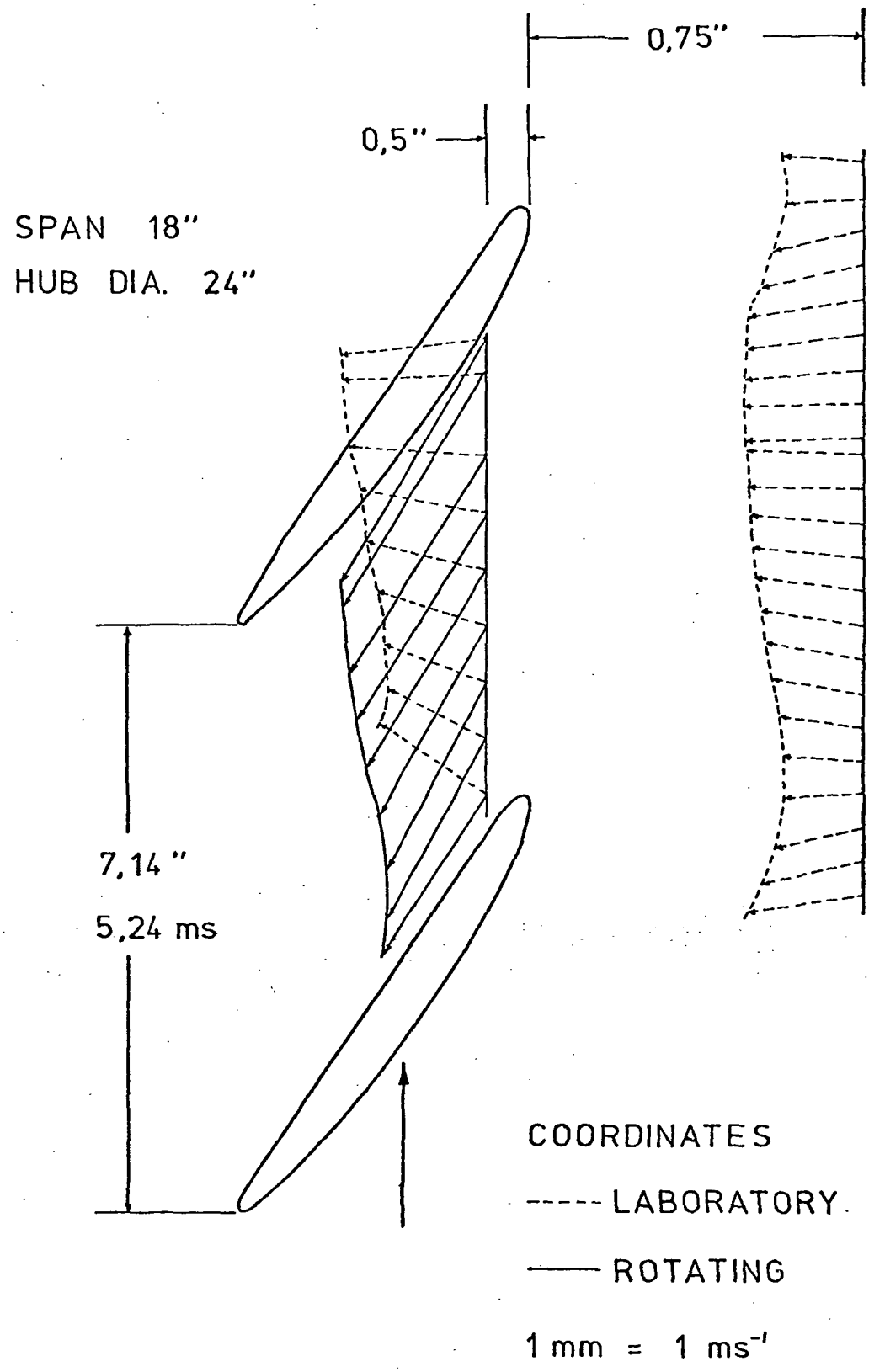

Figure 6. Axial Fan (60" dia.) Passage Traverse
5" From Tip Away From Design.

if the signal from each event/transit is sufficiently large to be classically regarded and the peak time treated as the digital event then the intrinsic broadening of the instrument tends to zero. (Actually, only a 1% minimum has thus far been achieved.) However, in the pure photon mode, where each event gives rise to one or more resolvable photons, the intrinsic broadening parameter depends on the spot diameter to separation ratio.

The application of correlation as an idea to transit anemometry is merely an efficient way of realizing the statistical distribution of transit times. We have talked about, and so far implied, the construction of auto-correlation functions. This is not the only approach to signal retrieval. For example, multichannel analysis may be used but most commercial machines are significantly slower than digital correlators. Also it may be shown that in all but a few special cases they are less efficient.

The most satisfactory way to use the transit anemometer signals is to cross correlate the signals obtained by viewing each spot with a different detector. This procedure maximizes the resolution of the correlation peak and further gives a "best estimate" of the background from uncorrelated events which must of course be removed before further statistical processing.

8.0 CONCLUSIONS

1. The concept of photon correlation is a powerful way of interpreting weak optical fields and extracting from them information formerly only derivable from much greater intensities of light.
2. The properties of light source and scatterer are indicated by photon bunching or specific statistical properties of the photon arrival intervals. The velocities of scatterers may be extracted from this.
3. The photon correlator may be thought of as a high resolution transform spectroscope with time resolution.
4. The instruments of this class may be used to measure motion, whenever it occurs. The applications so far have included molecular motion, cytoplasmic streaming, cellular motility, wind speed, velocity and turbulence in liquids and gases, in unsteady flames, compressors and turbines, afterburners and supersonic wind tunnels.

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APPENDIX

HINTS ON PHOTOMULTIPLIERS FOR PHOTON CORRELATION

- Use a high speed tube.
- Pick one with high gain - a large number of dynodes.
- Select a suitable cathode material for the application.
- Use an optical wedge to trap the incoming beam giving it more than one chance to strike the photocathode.
- Drive the extraction field (first grid) with a zener diode so that its behavior does not change with applied voltage.
- Screen the tube, electrically and magnetically (μ-metal).
- Decouple the last dynode stages with capacitors whose successive values increase by the same ratio as the operating stage gain.
- Use an adequate dynode chain current.
- Arrange the base components neatly, especially the anode; geometry matters at these speeds in pulse operation.
- Arrange the housing so that the heat generated in the dynode components does not immediately warm the cathode by conduction.
- Keep the tube on full rated voltage in total darkness for 48 hours prior to use and certainly after exposure to even dim room lighting, even with the voltage off.
- Arrange the tube operating voltage and the discriminator threshold to give the best freedom from afterpulsing and/or other sources of correlated secondary events.
- Select a good (free from correlation) photomultiplier tube. This may mean several tube types and several manufacturers - good tubes seem fairly rare and no one type or design has been found consistently good.
- Once a good tube always a good tube - a tube which is free from correlation does not seem to get worse with age with respect to this particular property. It may lose some cathode sensitivity with age.
- Always cap the tube when not in use - even though the voltage is off.

HINTS ON PHOTOMULTIPLIERS FOR PHOTON CORRELATION (Continued)

- Use correctly matched cable terminated at both ends. This fixes the operating load and consequently the pulse rise time. The tube transit time only matters in that its spread produces event time uncertainty - too small to matter with present correlators.

- Spread the input beam over the whole cathode on a restricted area tube and over the middle third on a large cathode tube.

- End window tubes are often better than side windows.

APPENDIX B

This appendix contains reprints of two papers and the title pages of two NASA Langley reports by W. T. Mayo, Jr., which describe the theory and aimplementation of the NASA-owned, SAI research correlator:

1. "Photon Counting Frequency Discriminator for LDV Systems," reprinted from Photon Correlation Spectroscopy and Velocimetry, edited by H. Z. Cummins and E. R. Pike, Plenum Publishing Corporation (1977).

2. "Photon Counting Processor for Laser Velocimetry," Applied Optics, Vol. 16, page 1157, May 1977.

3. "Study of Photon Correlation Techniques for Processing of Laser Velocimeter Signals," NASA CR-2780, February 1977.

4. "Advanced Photon Counting Processor for Low-Level LDV Signals," Final Report for NASA Contract NAS1-14384, October 1976.